Direct Phase-Resolved Simulation of Large-Scale Nonlinear Ocean Wave-Field

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LONG-TERM GOAL

The long-term goal is to develop a new powerful capability, which is named **SNOW** (**s**imulation of **n**onlinear **o**cean **w**ave-field), for predicting the evolution of large-scale nonlinear ocean wavefields using direct phase-resolved simulations. Unlike the phase-averaged approaches, SNOW models the key mechanisms such as nonlinear wave-wave, wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation in a direct physics-based context.

OBJECTIVES:

The specific scientific and technical objectives are to:

1. Develop effective physics-based modeling of wind forcing and wave-breaking dissipation for robust phase-resolved computation of nonlinear wavefield evolution.

2. Extend SNOW capabilities to handle high sea states for investigating the effect of very steep local waves upon evolution of wave statistics of nonlinear wavefields.

3. Extend SNOW to general finite water depth by including effects of bottom dissipation, fluid stratification, and variable current and bottom topography.

4. Speed up the computational algorithm underlying SNOW simulations for large spatial-temporal scale wavefields

5. Obtain direct validation and quantitative cross-calibration of SNOW simulations with phase-averaged wave model predictions and field/laboratory measurements.

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14. ABSTRACT
The long-term goal is to develop a new powerful capability, which is named SNOW (simulation of nonlinear ocean wave-field), for predicting the evolution of large-scale nonlinear ocean wavefields using direct phase-resolved simulations. Unlike the phase-averaged approaches, SNOW models the key mechanisms such as nonlinear wave-wave, wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation in a direct physics-based context.

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APPROACH

SNOW employs direct physics-based phase-resolved simulations for predicting the evolution of large-scale nonlinear ocean wavefields. SNOW is fundamentally different from the existing phase-averaged models in that, under SNOW, key physical mechanisms such as wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation are modeled, evaluated and calibrated in a direct physics-based context. In SNOW, detailed phase-resolved information about the wavefield is obtained, from which the statistical wave properties can also be derived.

SNOW is based on an extremely efficient high-order spectral (HOS) approach for direct computation of nonlinear ocean wavefield evolution. HOS is a pseudo-spectral-based method that employs Zakharov equation and mode-coupling idea and accounts for nonlinear wave-wave, wave-current, and wave-bottom interactions to an arbitrary high order (M) in wave/bottom steepness. This method obtains exponential convergence and (approximately) linear computational effort with respect to M and the number of spectral wave/bottom modes (N). HOS is an ideal approach for direct phase-resolved simulations of large-scale nonlinear wavefield evolution.

For data assimilation and/or specification of initial nonlinear wavefields in phase-resolved simulations, effective nonlinear wave reconstruction algorithms are developed and applied. The objective of wave reconstruction is to obtain detailed specifications (including phase) of a nonlinear wavefield, which matches given (directly or remotely sensed) wave sensed data or specified wave spectrum. Nonlinear wave reconstruction is achieved based on the use of optimizations with multiple-level (theoretical and computational) modeling of nonlinear wave dynamics. The validity of this methodology has been systematically verified against laboratory measurements and synthetic wave data for both long- and short-crested irregular wave-fields (Wu 2004; Wu *et al* 2008a, b). Large-scale SNOW computations are typically performed on high-performance computing platforms using up to $O(10^3)$ processors (Wu *et al* 2005).

WORK COMPLETED

The main focuses of the research are on the development and improvement of effective physics-based models for wind forcing input and breaking wave dissipation, extension of SNOW to account for density stratification effect, speedup of SNOW computations on high-performance computing platforms, and validation of SNOW simulations by direct comparisons against laboratory experiments and field measurement. Specifically,

- ***Modeling of wind forcing input***: Generation and growth mechanisms of wind waves are studied in the context of phase-resolved wavefield simulation. The wind forcing is modeled as an external surface pressure on ocean waves in SNOW simulations. The distribution of the surface pressure is parameterized according to the sheltering theory by adjustment to the observed spectral growth rates. The effectiveness and limitations of this model are investigated by quantitative comparisons with available laboratory and field measurements.
- ***Modeling of stratified fluid and bottom topography effects***: We extend SNOW simulations to littoral zones including stratified fluid and bottom topography effects. To consider the density stratification effect, SNOW is extended to multi-layer fluids. In particular, the resonant interactions among surface waves, interfacial waves, and bottom ripples are extensively investigated. The study provides an understanding of alternate mechanisms for the generation

of internal waves in the ocean, and establishes a framework for large-scale phase-resolved computations of internal wavefield evolution and interaction with surface waves (Alam, Liu & Yue 2008a, b).

- ***Efficient algorithm for steep waves***: We develop a highly efficient computational algorithm, so-called pre-corrected FFT method, for the simulation of fully-nonlinear steep wave dynamics. This approach is based on the boundary-element method formulation with the use of FFT algorithm for efficient evaluation of influence coefficients (Yan, Liu & Yue 2006). While much more complex in implementation, the PFFT algorithm requires ~O(N) computational effort, similarly to HOS. This algorithm is a useful complementary to SNOW for simulating fully-nonlinear dynamics of extreme waves (developed in large-scale ocean wavefield evolution) or steep/overturning waves in shallow water.
- ***Speedup of SNOW***: We continue to seek for high-performance computational resources to support the SNOW project. Last year, we were awarded a (three-year) DoD challenge project to support SNOW computations and development. We constantly improve the computational speed, scalability and robustness of the SNOW code on HPC platforms.
- ***Wave spectrum evolution by SNOW simulations***: We continue to perform large-scale phase-resolved SNOW computations to investigate the characteristics of statistic quantities of nonlinear ocean waves.

RESULTS

Validity of homogeneity assumption in prediction of wave spectrum evolution: In the phase-averaged approaches of ocean wave prediction, wavefield is assumed to be homogeneous. Understanding of the validity of this assumption is of importance to determination of the applicability of the phase-averaged approaches in practical environments. To address this issue, we apply direct phase-resolved SNOW computations to investigate the dependence of nonlinear wavefield evolution upon wave spectrum parameters. Our study confirms a recent finding based on the model equation (Dysthe *et al* 2003) that the homogeneity assumption is invalid/valid for narrow/broad band wavefields as a result of modulational instability effect.

Figure 1a shows the comparison of wave spectrum at the initial time $t = 0$ and after an evolution time $t/T = 240$ for a two-dimensional (long-crested) wavefield, where T represents the peak period. At the initial time, the wavefield is specified by a relatively narrowband Gaussian-type wave spectrum with effective steepness $\varepsilon = 0.1$ and bandwidth $\sigma = 0.1$ For comparison, the prediction based on the modified Nonlinear Schordinger (MNLS) equation by Dysthe *et al* (2003) is also shown. Clearly, the prediction by SNOW simulation compares well with that of MNLS. Both show that the wave spectrum is significantly widened in the nonlinear evolution of the wavefield. Figure 1b shows the time variation of spectrum bandwidth during the evolution. The bandwidth σ increases rapidly from the initial value of 0.1 to a steady-state value of ≈ 0.36 after an evolution of $t/T \approx 50$. Figure 2 plots the similar results for wavefields with a relatively broadband spectrum (effective steepness ε =0.1 and bandwidth σ = 0.3). For this case, bandwidth slightly increases (from 0.3 to 0.41) after an initial evolution of $t/T \approx 50$ and then remains steady. The change in wave spectrum during the evolution is much less apparent. These results indicate that modulational instability plays an important role in the evolution of nonlinear ocean wavefields with relatively narrowband wave spectra. Such an effect diminishes for wavefields with broadband wave spectra.

Nonlinear effects in wave height distribution of three-dimensional (short-crested) wavefields: Due to nonlinearities in surface wave dynamics, the prediction of ocean wave statistics based on linear wave theory and the assumption of Gaussian random process is known to deviate from field measurements (Mori, Liu & Yasuda 2002; Socquet-Juglard *et al* 2005). It is of fundamental interest to understand and quantify the nonlinear effects upon wave statistical quantities in nonlinear ocean wavefield evolution. In this study, we apply large-scale phase-resolved SNOW computations to investigate this problem with the focus on characterizations of wave height distribution of short-crested wavefields. Our study shows that in general, Rayleigh distribution (based on linear theory) underestimates the exceeding probability of crest height, especially for large heights with $R/\eta_{\mathrm{rms}} \geq 2$ where R represents the crest height and η_{rms} the standard deviation of the wave elevation. Tayfun distribution (based on the second-order theory) properly captures the nonlinear effects for wavefiedds with wide spreading angles. As the effective steepness increases and/or spreading angle decreases, higher-order nonlinear effects (higher than the second order) become stronger, and Tayfun distribution loses its validity with a significant underestimation of large crest height occurrence.

Figure 3 shows the distribution of exceeding probability of crest heights of three-dimensional wavefields with various wave spectrum parameters. The results are obtained from SNOW simulations at t/T =100 for wavefields with significant wave height H_s =10 m, peak period T=12 s and four combinations of enhancement parameter γ and spreading angle Θ: γ, Θ = 1.0, 80$^{\mathrm{o}}$; 5.0, 80$^{\mathrm{o}}$; γ = 1.0, Θ =18$^{\mathrm{o}}$, and 5.0, 18$^{\mathrm{o}}$. SNOW simulations are performed in a computational domain of about 30km × 30km with nonlinearity order M =3. For comparison, the predictions by Rayleigh distribution (linear theory) and Tayfun distribution (second-order theory) are also shown. For all four cases, it is seen that Rayleigh distribution significantly underestimates the occurrence of large crest heights (with $R/\eta_{\mathrm{rms}} \geq$ 2). For wavefields with wide spreading (Θ = 80$^{\mathrm{o}}$), the prediction by Tayfun distribution is quite reasonable as it agrees well the SNOW computation. For the wavefields with narrow spreading (Θ = 18$^{\mathrm{o}}$), although better than Rayleigh distribution, Tayfun distribution also underestimates the probability of large crest height as higher-order effects become important. Such higher-order effects (higher than second order) become stronger for wavefieds with smaller Θ and/or larger γ

IMPACT/APPLICATIONS

This work is the first step toward the development of a new generation of wave prediction tool using direct phase-resolved simulations. It augments the phase-averaged models in the near term and may serve as an alternative for wave-field prediction in the foreseeable future.

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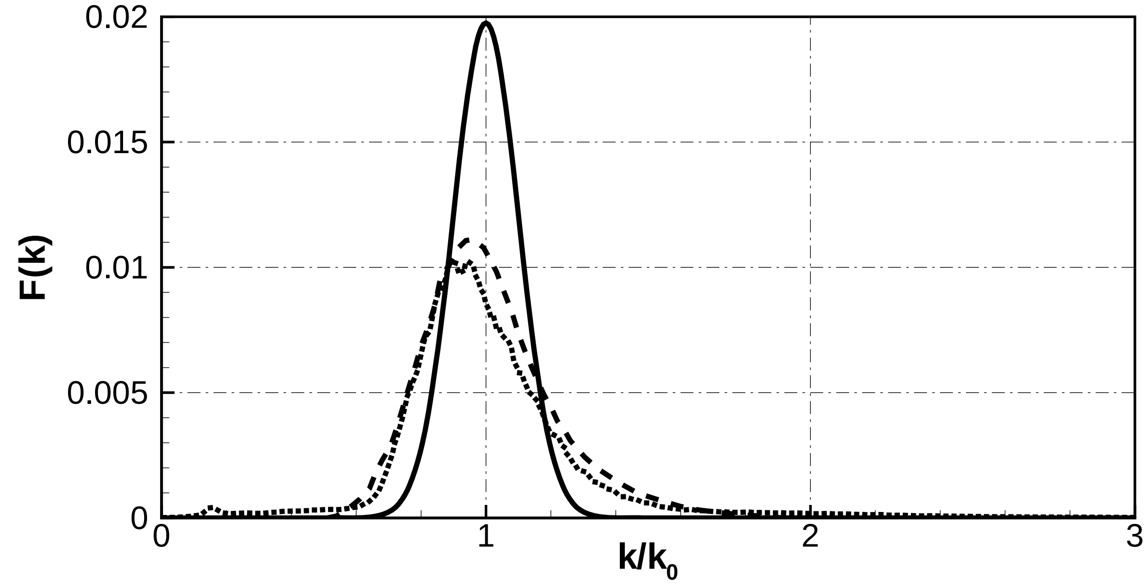

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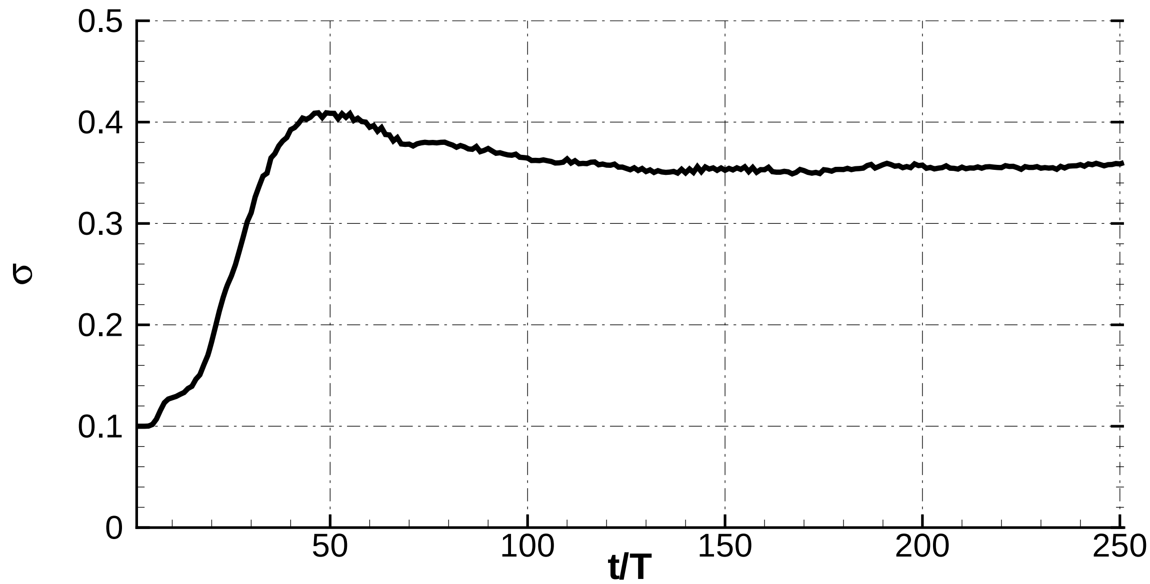

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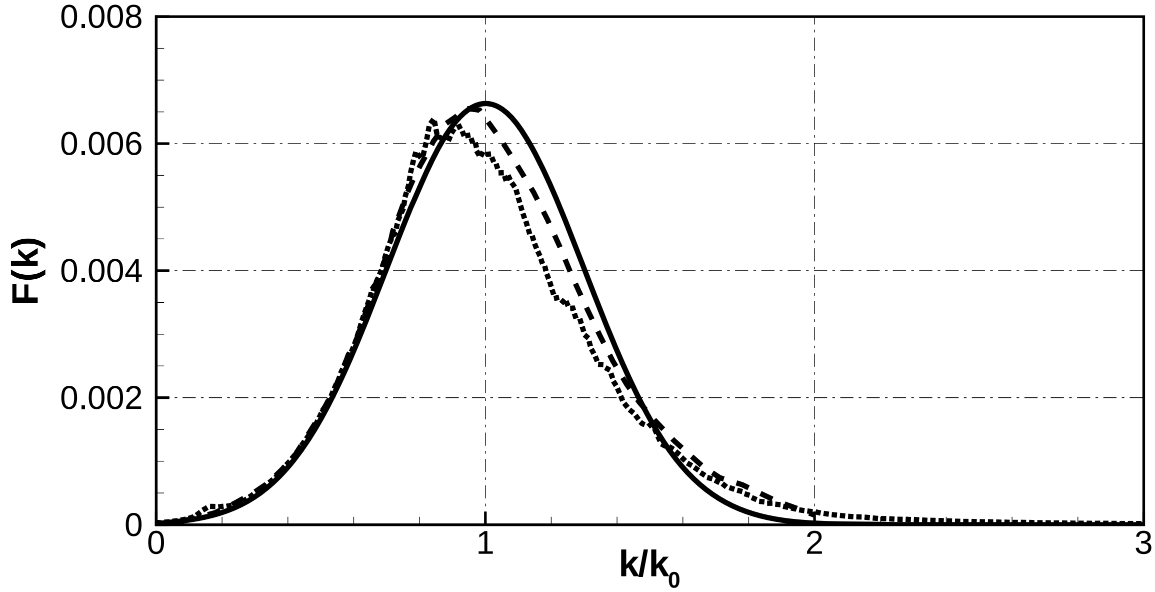
Figure 1. (a) Comparison of wave spectrum at t = 0 (solid line) and t/T =240 (SNOW computation: dot line; MNLS prediction of Dysthe et al (2003): dash line) in the evolution of a nonlinear wavefield initially specified by a relatively narrowband Gaussian-type wave spectrum with effective steepness $\varepsilon = 0.1$ and bandwidth $\sigma = 0.1$, and (b) time variation of spectrum bandwidth in the evolution of the wavefield, obtained by SNOW computation.



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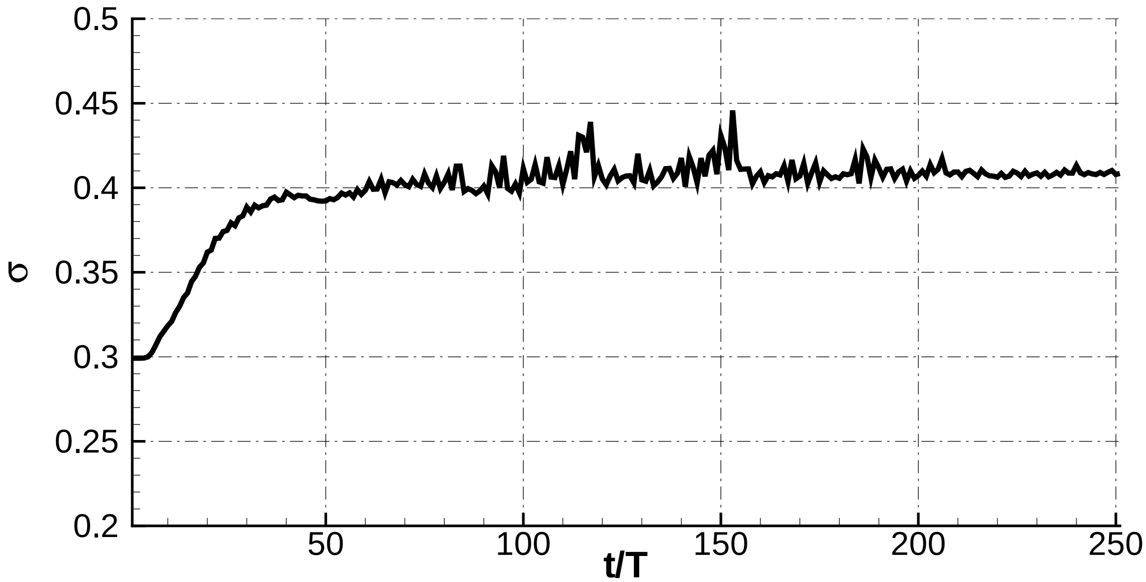

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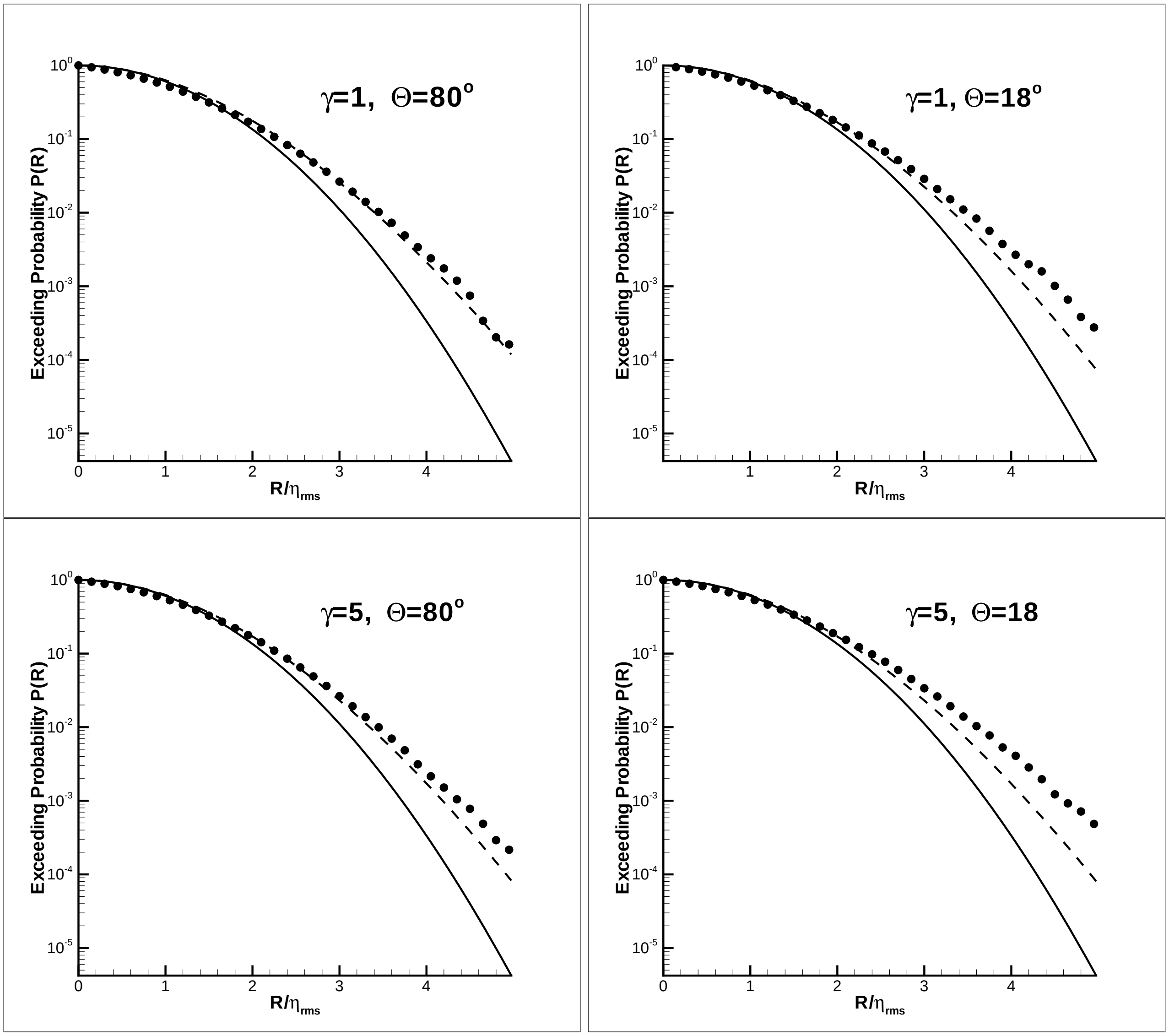

Figure 3. Comparison of exceeding probability of crest heights for various wave spectrum parameters. The results are obtained from phase-resolved SNOW simulations at t/T =100 for wavefields with significant wave height H_s =10 m, peak period T=12 s and four combinations of enhancement parameter γ and spreading angle Θ: γ = 1.0 and Θ =80^o (top left), γ = 5.0 and Θ =80^o (bottom left), γ = 1.0 and Θ =18^o (top right), and γ = 5.0 and Θ = 18^o (bottom right). The plotted are the results by SNOW simulation (bullets); Rayleigh distribution (solid line); and Tayfun distribution (dashed line).